Small Solar Electric Propulsion Spacecraft Concept for Near Earth Object and Inner Solar System Missions

Jared J. Lang[1], Thomas M. Randolph[1], Timothy P. McElrath[1], John D. Baker[1], Nathan J. Strange[1], Damon Landau[1], Mark S. Wallace, J. Steve Snyder[1], Jamie S. Piacentine[1], Shane Malone[2], Kristen M. Bury[2], William H. Tracy[3]

[1] *Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena CA 91109*

[2] *NASA Glenn Research Center, 21000 Brookpark Road, Cleveland OH 44135*

[3] *NASA Johnson Space Center, 2101 NASA Parkway, Houston TX 77058*

Abstract. Near Earth Objects (NEOs) and other primitive bodies are exciting targets for exploration. Not only do they provide clues to the early formation of the universe, but they also are potential resources for manned exploration as well as provide information about potential Earth hazards. As a step toward exploration outside Earth's sphere of influence, NASA is considering manned exploration to Near Earth Asteroids (NEAs), however hazard characterization of a target is important before embarking on such an undertaking. A small Solar Electric Propulsion (SEP) spacecraft would be ideally suited for this type of mission due to the high delta-V requirements, variety of potential targets and locations, and the solar energy available in the inner solar system.

Spacecraft and mission trades have been performed to develop a robust spacecraft design that utilizes low cost, off-the-shelf components that could accommodate a suite of different scientific payloads for NEO characterization. Mission concepts such as multiple spacecraft each rendezvousing with different NEOs, single spacecraft rendezvousing with separate NEOs, NEO landers, as well as other inner solar system applications (Mars telecom orbiter) have been evaluated. Secondary launch opportunities using the Expendable Secondary Payload Adapter (ESPA) Grande launch adapter with unconstrained launch dates have also been examined.

Keywords: Near Earth Objects, NEO, SEP, ESPA

1. Introduction

The NEO Surveyor mission provides a unique opportunity to determine the physical, orbital and surface properties of the various classifications of asteroids within a single mission. Although several different classifications of asteroids have been defined, most NEAs fall into the three categories: C, S and M-class asteroids. The classification of asteroids into these categories is defined through ground and space-based observations of spectral shape, color and albedo[1]. The Surveyor concept has the ability to launch up to four separate spacecraft to provide in-situ characterization of the three classes of asteroids with a single launch as a secondary payload. In addition to studying the physical properties of different classifications of NEOs the Surveyor spacecraft can also be used as a precursor mission to potential targets for future human exploration.

Launched aboard the ESPA Grande secondary launch adapter, the Surveyor mission would deliver one to four spacecraft into a low energy orbit, where the onboard SEP system will deliver the spacecraft to their prospective targets. Once at the target, the SEP system will rendezvous with the body, providing an opportunity to gather in-situ data. Three variations of the spacecraft, which will be discussed in more detail, have been designed to provide different levels of detail about the body.

The Surveyor spacecraft has been developed for flexibility. Designed out of commercially available, off-the-shelf parts (COTS) the spacecraft could be built for a launch as early as 2015. In addition to NEO missions, the Surveyor bus design allows for exploration of Mars and Venus with no modification to the original spacecraft design.

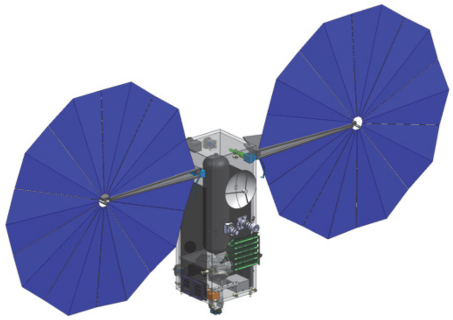

Figure 1. Surveyor spacecraft is a small, but capable spacecraft

1. Spacecraft

Surveyor, shown in **Error! Reference source not found.**, consists of one to four single-string spacecraft built out of COTS components and is capable of carrying up to 30 kg of payload on each spacecraft. Redundancy is achieved at a mission level by launching multiple spacecraft as a secondary payload. Three variations, described in Table 1, of the spacecraft have been designed to deliver different types of payloads to the target, though only the baseline mission will be described in more detail. These variations were developed to access an array of different targets, however the baseline bus may not require modification to perform the other mission objectives for specific targets. The baseline mission consists of a small, three hundred kilogram, 3-axis stabilized spacecraft capable of providing high-resolution images of the asteroid surface, determining the surface characteristics and the radiation environment about the body. The other variations include a design to rendezvous with multiple NEOs using the same spacecraft and the addition of a surface interaction package.

1.1 Propulsion

A key advantage of the Surveyor concept is the use of a flight-proven commercial SEP system that enables the flexibility to access several different targets with almost no constraint on launch dates. Developed for GEO communication satellites, commercially available EP systems such as the SPT-100[2] or BPT-4000[3] are nearly perfectly sized for the electrical power requirements and lifetime to meet the Surveyor mission goals.

In addition to the SEP system, the Surveyor spacecraft requires a Reaction Control System (RCS) to provide momentum dumping, attitude control, and additional agility for the close proximity options. Cold gas xenon and hydrazine systems were evaluated as part of the RCS trade study, however the mass difference between the two propellants was relatively small for the baseline mission. For this reason, the xenon fed cold gas system was chosen due to the added complexity of a separate monopropellant system.

1.2 Power

Surveyor is powered by two ATK UltraFlex solar arrays[4] similar to those flown on Phoenix providing roughly 2 kW of power at 1 AU. For potential NEO trajectories that require thruster activity at solar distances of less than 0.75 AU, wing off pointing may be required to prevent the cell operating temperature from exceeding its temperature limit. Preliminary analysis has shown that distances greater than 0.75 AU will not require wing off pointing for thermal purposes, however it may be employed to reduce

Table 1. Surveyor variations require little modification for increased science return

Option Variations			
	Option 1 - Baseline	**Option 2 - Mulitple Targets**	**Option 3 - Surface Interations**
Mission Operations			
Number of Spacecraft Launched	1 to 4	2	1 to 4
Number of Targets (per S/C)	1	2	1
Additional Operations	All measurements obtained by proposed operations	Spacecraft will visit two targets, characterizing each using the same operations proposed	Spacecraft will perform TAG manuever, coming close enough to the surface to fire projectiles and image results
Eaxmple Payload	Visual Imager, IR Imaging Spectrometer, Radiation Experiment	Visual Imager, IR Imaging Spectrometer, Radiation Experiment, Radar	Visual Imager, IR Imaging Spectrometer, Radiation Experiment, Surface Interaction Package
Spacecraft Changes from Baseline	-	Larger SEP system, Larger Solar Arrays	Larger Reaction Wheels, Monopropellant Hydrazine RCS

the peak voltage if required by the SEP system. **Error! Reference source not found.** provides the array output power as a function of solar distance as required for the NEO Surveyor mission.

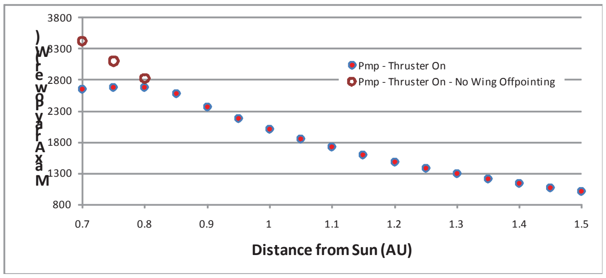

Figure 2. Surveyor solar arrays are perfectly sized for the SEP system

In addition to the solar array power generation, power storage is required for critical components during the launch phase. A non-rechargeable 13 Amp-hour lithium-sulfur dioxide primary battery has been estimated to provide sufficient power for critical components until the solar arrays can be deployed in orbit.

1.3 Electrical Power System

The High Voltage Electrical Assembly (HVEA) provides high power-management for spacecraft equipped with SEP. Modifications to the HVEA flown on the Dawn spacecraft are planned for Surveyor. The Dawn HVEA is sized for higher-power applications and includes significant internal redundancy and fault protection that will not be required for this mission. The HVEA will take the high voltage output from the solar arrays and distribute the high voltage power to the SEP Power Processing Unit (PPU) and converted low voltage power to the spacecraft Command and Data Handling (C&DH) system.

1.4 Command and Data Handling

The spacecraft C&DH architecture is based on a commercially available Broad Reach Engineering (BRE) design. The single-string, Rad-750 based architecture provides the mission with 8 Gbits of flash memory, telemetry and control interfaces for the spacecraft. RS-422/RS-485 ports are used to send commands and data to the Inertial Measurement Unit (IMU), reaction wheels, and the SEP PPU. Discreet and analog signals provide state information of latches, temperature and other telemetries. A Mil-Standard 1553B bus is used to send commands and data to the star tracker and the Small Deep Space Transponder (SDST) for direct to Earth communication (DTE).

1.5 Guidance and Control

The Guidance and Control Subsystem provides 3-axis attitude and translational velocity directional control. Attitude determination is accomplished via a single Galileo AA-STR star tracker supplemented with a Northrop Grumman LN-200S IMU. The IMU is used to propagate the attitude estimate during tracker outages. Eight Adcole Coarse Sun Sensors are used to estimate body relative Sun position and are used post launch vehicle separation to achieve a power positive spacecraft state. Incremental translational velocity measurement is obtained with an Allied Signal QA 3000-30 accelerometer. Integrated accelerometer measurements are used to cut off thrusting of SEP system.

Three Goodrich reaction wheels similar to those flown on GRAIL[5] are mounted in a pyramid configuration to provide attitude control, slewing of the spacecraft, and angular momentum storage. The reaction wheel assembly (RWA) momentum management is accomplished via thrust vector control when the SEP is thrusting. Ten 0.2N MOOG 58-132 cold gas thrusters are used to null spacecraft rates following launch vehicle separation. These thrusters are also used to maintain attitude during contingencies and manage reaction wheel angular momentum when the SEP is not thrusting.

1.6 Telecommunication

Communication to Earth is achieved using an X-band uplink/downlink for science, command and telemetry. The single-string system utilizes a Small Deep Space Transponder (SDST)[6], 100 W Traveling Wave Tube Amplifier (TWTA), diplexer and switches connected to a 0.5 m high gain antenna (HGA) and two MER heritage low gain antennas (LGA). Nominal science data is downlinked from the NEOs via the HGA at a rate of 40 kbps to a 34m Deep Space Network (DSN) station. The LGAs provide lower data rate transmission during the initial cruise when the spacecraft is close to Earth.

1.7 Structure and Thermal

Surveyor employs the standard structural design used on all JPL built spacecraft. The aluminum primary structure provides support for the propulsion system, avionics and RWA. External aluminum honeycomb panels are used to support telecom, instruments and thermal radiators. The spacecraft mechanisms consist of commercially available solar array drive assemblies and an engine gimbal, providing 2-axis articulation of the solar arrays and SEP thruster.

Spacecraft thermal control is obtained using two 2 m^2 thermal radiators mounted on each side of the spacecraft. Due to the variation in the heating environment between 0.7 and 1.5 AU, the spacecraft utilizes thermal louvers mounted atop the radiator to help control the heat dissipation of the electronics. MLI, heaters and temperature sensors will monitor and control the temperature of critical components within the spacecraft including avionics and propellant lines.

1.8 Variations

Spacecraft variations, shown in **Error! Reference source not found.**, have been developed to meet the various mission architectures defined in **Error! Reference source not found.**. These missions can be placed into two categories: surface interaction and multiple targets. Surface interaction missions would require the spacecraft to either fly very close (within a meter) or actually touch the surface. A surface interaction mission would necessitate a more agile spacecraft, forcing an upgrade from the cold gas RCS system to a blowdown monopropellant hydrazine system. Automated guidance, navigation and control (AutoGNC) would use the more capable RCS to provide attitude and translational velocity control near the target surface. In addition to the improved spacecraft control, an upgraded IMU would be required to provide more accurate attitude determination during close proximity operations.

Missions designed to send a single Surveyor spacecraft to multiple target bodies would require a longer life propulsion system, such as the commercially available BPT-4000 Hall Effect Thruster, to accommodate the increased delta-V of the mission. The BPT-4000 has a higher power requirement thus increasing the solar array size and structure mass.

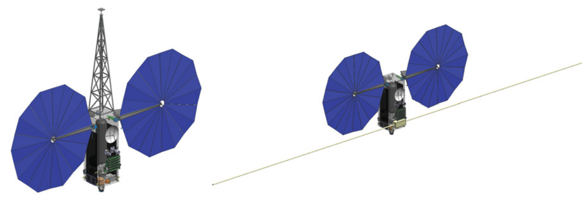

Figure 3. Variations to the Surveyor bus can be easily accommodated

2. Mission Operations

The Surveyor spacecraft has the capability to rendezvous with several NEOs, Venus or Mars after a low energy Earth departure and up to 5 km/s of delta-V. For any target, the spacecraft propulsion system is used to obtain the target's orbit shape and phasing within the orbit. Although trajectory trades can be done to reduce the required delta-V to reach the targets, higher inclination NEOs and main belt asteroids are out of reach for this class of spacecraft.

2.1 Secondary Launch Opportunities

As a secondary payload[7], the Surveyor bus will utilize additional propellant in the second stage to boost the ESPA Grande launch adapter and spacecraft to a characteristic energy (C3) of between -1 (for lunar phasing) and 2 (for direct injection). If placed into a negative C3 trajectory, the spacecraft can utilize lunar flybys to increase the energy and phase the orbit in the direction of the target. Although lunar flybys will increase the flight times by up to 6 months, it will provide the spacecraft an opportunity to increase the C3 in the desired direction to intercept the targets regardless of the launch period. When the LV performance and primary payload orbit requirements permit it, another approach is to use the upper stage of the launch vehicle to place the spacecraft into a positive C3, relying on the SEP system to perform the orbit shaping and phasing. Figure 4 shows the launch configuration of four Surveyor spacecraft as secondary payloads.

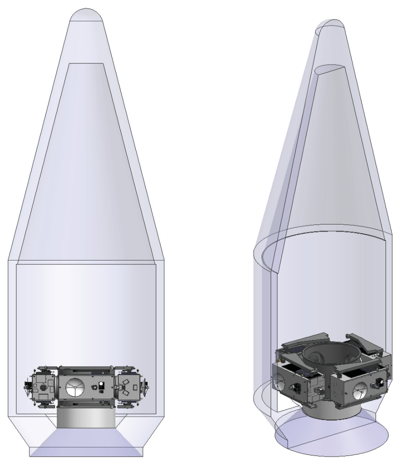

Figure 4. Four Surveyor spacecraft can be launched as a secondary payload

2.2 Near Earth Asteroids

For NEOs, the mission design is optimized to reduce delta-V by shaping and phasing the trajectory simultaneously. For shorter flight times, the phasing dominates the total delta-V usage. In order to reduce the delta-V required for the mission, flight times are increased to between two and three years, depending on the target. For multiple NEO missions, each spacecraft will be required to phase their orbits by up to 180 degrees, providing access to targets either ahead of or trailing behind the Earth. Phasing for these NEOs will be done by dropping to a lower period orbit to catch up to an object or boosting to a higher period to fall behind one.

In the Apophis example shown in Figure 5, the target is in a lower-period orbit requiring the spacecraft to drop below the Apophis period to catch up to it, and then returns to the Apophis period in the final rendezvous thrusting.

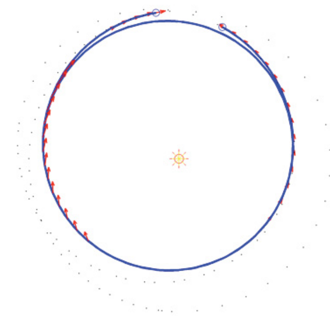

Figure 5. Mission trajectories to Apophis can be accomplished in under two years

Once in the NEO proximity, the spacecraft is unable to orbit the target since the asteroid is insufficiently large to allow stable orbits to exist. The ratio of solar radiation pressure to gravity is large enough that a spacecraft in orbit is effectively blown off course by solar radiation pressure. Surveyor combats this by entering into a proximity operations phase that is broken down into two components: multiple flybys and ping-pongs.

The multiple flybys phase has three primary objectives: to allow a detailed survey of the near-asteroid environment, to generate the first shape models of the asteroid, and to get a first estimate of the asteroid's mass. During this phase, the spacecraft flies past the asteroid and uses the SEP system to execute a maneuver to turn around. This process is repeated as the spacecraft flies back and forth about the target. For Apophis, the flybys are at a relatively low velocity (~2.5 m/s) and relatively low altitude (~100 km). The turn-around maneuvers are approximately 5 m/s in magnitude and constitute the largest portion of the proximity operations phase fuel budget.

Ping-pongs are similar to multiple flybys in that the asteroid never energetically captures the spacecraft and the maneuvers reverse the spacecraft momentum. Ping-pongs differ from multiple flybys in that they are much slower (~0.1 m/s vs. ~2.5 m/s) and the turn-around maneuvers are performed much closer to the asteroid (10s of km vs. 100s of km). The ping-pongs offer less altitude variation and greater variation in solar phase angle relative to the multiple flybys. This makes them ideal for high-resolution global mapping or radar sounding campaigns. Figure 6 provides graphical representation of the Multiple Flybys and Ping-Pongs about Apophis.

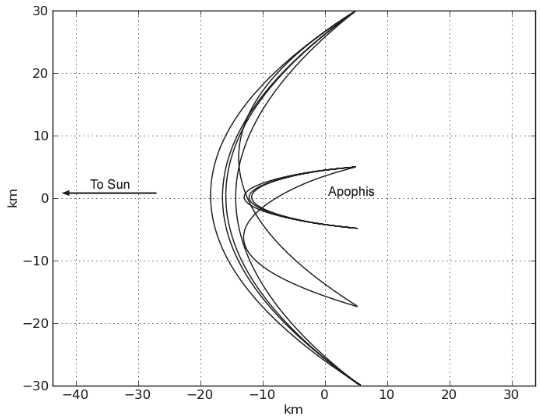

Figure 6. Proximity operations about Apophis provide a ideal platform for target characterization

2.3 Planetary Targets

Mars and Venus trajectories have been developed for a mission using the Surveyor spacecraft. Trajectories to one of these planets typically use ballistic transfers, restricting the launch opportunities as a secondary payload. However, an Earth flyby could be used to build up Earth-relative hyperbolic excess velocity (V∞), allowing the mission to depart on one of the typical ballistic Earth-Mars or Earth-Venus transfers. In the examples shown in Figure 7, the trajectory allows for direct transfers from the Earth to Mars or Venus on a near-Hohmann due to the choice of a near-optimum launch date. However, remaining in an intermediate-period orbit allows non-optimum launch dates to reach both planets in less than 3 years. On arrival to the body, the V∞ can be removed either by pure thrusting or, in the case of the example trajectories, by adding a Mars/Venus flyby. Though this additional maneuver adds trip time to the overall mission, it allows for the Surveyor spacecraft to access a wider range of targets with modest delta-V and flight times.

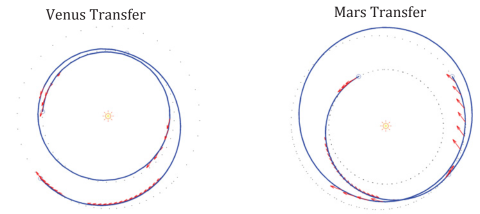

Figure 7. Surveyor can provide interesting missions to Venus or Mars with no modification to the spacecraft

3. Conclusion

NEO Surveyor is a unique, innovative mission architecture that promotes significant science opportunity at several different targets. The Surveyor SEP system provides the flexibility for the mission to be launched as a secondary payload aboard the ESPA Grande launch adapter and provides access to several classes of NEOs, Mars and Venus. In addition to the revolutionary science that Surveyor is capable of, it provides an opportunity to take the first step to human exploration outside of the Earth's sphere of influence.

Acknowledgements

The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration,

References

[1] Binzel, R.P., Lupishko, D.F., Di Martino, M., Whiteley, R.J., Hahn, G.J. "Physical properties of near-Earth objects", In Asteroids III. Univ. of Arizona Press, Tucson, AZ, pp. 255–271, 2002

[2] C. Garner, J. Brophy, J. Polk, and L. Pless, "Performance Evaluation and Life Testing of the SPT-100", AIAA-94-2856, 1994

[3] B. Welander, C. Carpenter, K. de Grys, R. Hofer, T. Randolph, D. Manzella, "Life and Operating Range Extension of the BPT-4000 Qualification Model Hall Thruster", AIAA-2006-5263, 2006

[4] B. Spence, S. White, A. Jones, N. Wachholz, P. Cronin, T. Gregory, P. Barker, T. Allmandinger, N. Mardesich, M. Piszczor, P. Sharps, N. Fatermi, "UltraFlex-175 Solar Array Technology Maturation Achievements for NASA's New Millennium Program (NMP) Space Technology 8 (ST8)", IEEE 04060045, 2006

[5] T. Hoffman, C. Bell, H. Price, “Systematic Reliability Improvements on the GRAIL Project”, IEEE 05446888, 2010
[6] C. Chen, S. Shambayati, A. Makovsky, F. H. Taylor, M. Herman, S. Zingales, C. Nuckolls, and K. Siemsen, “Small Deep Space Transponder (SDST) DS1 Technology Validation Report”, JPL Publication 00-10, Jet Propulsion Laboratory, Pasadena, California, 2000.
[7] P. Wegner, J. Ganley, J. Maly, “EELV Secondary Payload Adapter (ESPA) Providing Increased Access to Space”, IEEE 931218, 2001